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Modification of the GRAMI Model for Cotton

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ABSTRACT

A new version of the GRAMI crop model capable of being calibrated within season was developed and tested for cotton (*Gossypium hirsutum* L.) production in semiarid regions. The model was first verified using field data obtained at Halfway, TX, USA in 2002. The model was then validated using data sets obtained at Lamesa, TX in 1999 and 2001 and at Lubbock, TX in 2002 and 2004. Simulated values of cotton growth and lint yield showed reasonable agreement with corresponding measurements under irrigated conditions. The new model not only has simple input requirements but is also easy to use. Thus, it promises to have applicability to be expanded to other semiarid regions for irrigated cotton production and to have applicability to regional cotton growth monitoring and lint yield mapping projects.

Remote sensing and modeling are different techniques useful for the evaluation of crop growth and yield (Maas, 1992). Remote sensing imagery can provide information for almost any spot on the earth's surface but can provide information valid only at the time of image acquisition. Models can provide a continuous description of crop condition during the growing season although they may not provide information as accurately as that provided by remote sensing. However, by combining the advantages of remote sensing and simulation modeling, the strengths of one technology may make up for weaknesses in the other (Maas, 1992).

There have been previous efforts to combine these different techniques. One such effort was GRAMI (Maas, 1992), a crop model that uses remote sensing data and is applicable to gramineous crops such as wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), and sorghum [*Sorghum bicolor* (L.) Moench]. GRAMI includes a within-season calibration method allowing the model simulation to fit measured values using an iterative numerical procedure. Based on a comparison between measured and simulated values, model parameters and initial conditions that affect crop growth can be changed. The model is then re-executed to produce a new set of simulated values that minimizes the error between simulated leaf area and values of leaf area obtained from remote sensing. An advantage of this procedure is that it can use infrequent observations to calibrate the model. These observations can be obtained through nondestructive techniques such as remote sensing (Maas, 1992).

The objective of this study was to extend the applicability of GRAMI to simulation for irrigated cotton production. The model was developed and verified using field data from irrigated commercial cotton fields in the Texas High Plains, USA. The model was validated using field data from independent sites in this region, and its applicability will be discussed.

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MATERIALS AND METHODS

Field Data

Model Development and Verification

Cotton field data to develop and verify the model were collected from farmers' fields in the Texas High Plains during the summer of 2002. Three cotton fields were selected (referred to as #26, #28, and #33) for this study. They were circular with about 45 ha for each. The latitude and longitude of each field were 34°2′41″ N, 102°2′18″ W for #26; 34°4′6″ N, 102°11′10″ W for #28; and 34°11′31″ N, 102°1′16″ W for #33. The soils were Brownfield fine sands for #26 and #28 and a Pullman clay loam, 0 to 1% slopes, for #33 (soil survey for Lamb County, TX, issued in 1962, and Hale County, TX, issued in 1974, USDA Soil Conserv. Serv.). Plant growth and development data, including plant height, leaf area index (LAI), and aboveground dry mass (AGDM), were measured every 2 wk at four different locations in each field. The cotton variety Paymaster 2326 BG/RR (Delta and Pine Land Co., Scott, MS) was planted on 16 May at 1.0-m row spacing in all locations. During the cotton growing season (13 May–20 October), average photosynthetically active radiation (PAR) was 9.83 MJ m^{-2} d^{-1}, and rainfall was 107.2 mm. Irrigation was applied using low-energy precision application (LEPA).

In each plot, 10 representative plants were selected, cut, and transported to the laboratory to measure several plant growth parameters, including leaf area; number of main-stem nodes, squares, and bolls; and leaf, stem, square, and boll dry mass. Leaf area was measured using a LI-3100 area meter (LI-COR Inc., Lincoln, NE). Leaf area index was calculated as leaf area per plant divided by ground area per plant. Plant samples were separated into leaves, stems, squares, and bolls and dried at 70°C for 72 to 168 h, depending on sample sizes to obtain dry mass.

Digital photographs (Fig. 1) of each plot were taken on days when field sampling was done using a digital camera (Digital Still Camera, Dycam Inc., Chatsworth, CA) positioned over the plot. The digital images were processed to calculate ground cover (GC) using image-processing software (Adobe Photoshop 7.0, Adobe Systems Inc., San Jose, CA). To calculate GC, the digital image was cropped using the software to include plant stand rows with a same area that represent the actual plant population. Then, plant-occupied area was selected and referenced for the pixel values. The GC was calculated as the pixel ratio of plant occupied area to total ground area of the image.

Abbreviations: AGDM, aboveground dry mass; GC, ground cover; GDD, growing degree days; LAI, leaf area index; LEPA, low-energy precision application; PAR, photosynthetically active radiation; RMSE, root mean squared error.

Fig. 1. Taking an overhead digital photograph using DyCam in the field (left) and the corresponding digital image (right).

Validation Data

Four years of data from two fields were used. Two data sets were collected in 1999 and 2001 from a 45-ha field at the Texas A&M University Agricultural Research farm (32°16′ N, 101°56′ W) near Lamesa, TX (Li et al., 2001; Bronson et al., 2003). The other data sets were collected in 2002 and 2004 from the field of the USDA-ARS Plant Stress and Water Conservation Laboratory at Lubbock, TX (Wanjura et al., 2004). The soils of both sites were Amarillo sandy loams. Cotton variety Paymaster 2326 RR was planted on 10 May in 1999 and 28 May in 2001, and Paymaster 2326 BG/RR was planted on 13 May in 2002 and 2004. Rainfall from May to mid-September was 130 mm in 1999 and 128 mm in 2001 at Lamesa and 186 mm in 2002 and 218 mm in 2004 at Lubbock. Irrigation was applied using a LEPA irrigation system at Lamesa and a subsurface drip irrigation system at Lubbock.

Model Formulation

The four processes (Fig. 2) involved in simulating daily cotton crop growth were (i) calculation of growing degree days (GDD), (ii) absorption of incident radiation energy by leaves, (iii) production of new dry mass by the leaf canopy and determination of boll production, and (iv) determination of LAI partitioning of new dry mass. In this section, the mathematical equations to estimate these processes are described.

The accumulation of GDD is calculated as follows:

$$\Delta D = \mathrm{Max}(T - T_b, 0) \qquad [1]$$

where ΔD is the daily change of GDD, T is the average daily air temperature (°C), and T_b is a base temperature specific to a crop species. The value for T_b is 15.6°C (Wanjura and Supak, 1985). The value for ΔD is zero when T is less than or equal to T_b.

The daily increase in AGDM is calculated as:

$$\Delta M = \varepsilon \cdot Q \qquad [2]$$

where ΔM is the daily increase in AGDM, ε is the radiation use efficiency (RUE) value specific for a given crop, and Q is the daily total PAR (MJ m^{-2}) absorbed by the crop canopy (Rosenthal et al., 1989; Jones and Kiniry, 1986; Charles-Edwards et al., 1986). The RUE (ε) was estimated as the slope of the regression equation between the amount of dry matter produced and the amount of light energy absorbed over a given time period (Charles-Edwards, 1982; Rosenthal and Gerik, 1991). The slope of the regression line determined with data from three fields (#26, #28, and #33) is the estimated cotton ε of 2.3 g MJ^{-1} (Ko, 2004). This value is lower than the value of 2.55 g MJ^{-1} for irrigated Acala SJ-2 reported by

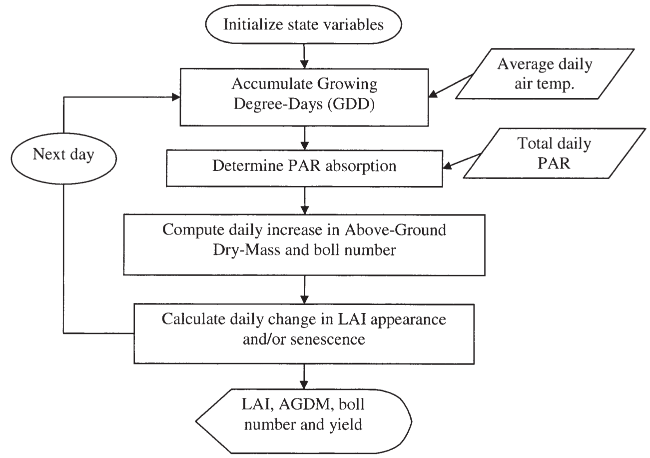

Fig. 2. Daily cotton growth processes used in the model (modified from Maas, 1993a). AGDM, aboveground dry mass; LAI, leaf area index; PAR, photosynthetically active radiation.

Howell and Musick (1985) and higher than the values of 1.3 g MJ^{-1} for Tamcot and 1.5 g MJ^{-1} for Acala reported by Rosenthal and Gerik (1991). However, it is within the range (2.0–2.3 MJ^{-1}) for common C_3 plants described by Gallagher and Biscoe (1978). Absorption of PAR is calculated as:

$$Q = \beta \cdot R \cdot (1 - e^{-k \cdot \mathrm{LAI}}) \qquad [3]$$

where R is the incident daily total solar irradiance (MJ m^{-2}), β the fraction of total solar irradiance that is PAR, and k a light extinction coefficient specific for a given crop (Charles-Edwards et al., 1986). The value for β is 0.45 (Monteith and Unsworth, 1990). According to the relationship between the measured GC and LAI data from the three fields, the cotton canopy covered ≈90% of the fields when it reached the maximum LAI (Fig. 3). The k value was estimated according to the relationships between the proportion of the daily light energy intercepted by a crop canopy ($Q_0 = 1 - e^{-k \cdot \mathrm{LAI}}$) and k values (Fig. 4A), assuming that the Q_0 values agree with cotton canopies of the measured fields at ≈0.9 when LAI peaks. The natural logarithm of the proportion of the incident

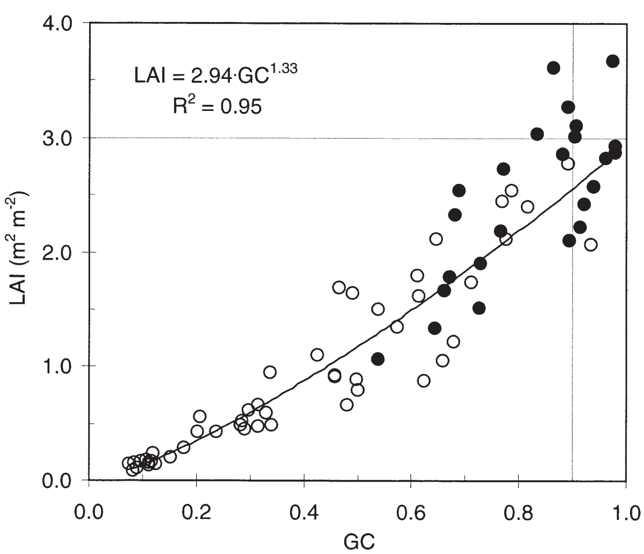

Fig. 3. Relationship between leaf area index (LAI) and ground cover (GC) from Field #26, #28, and #33. Open circles are data points before maximum LAI, and filled circles are data points at and after maximum LAI. Horizontal and vertical dotted lines represent average values of LAI and GC at maximum crop canopy.

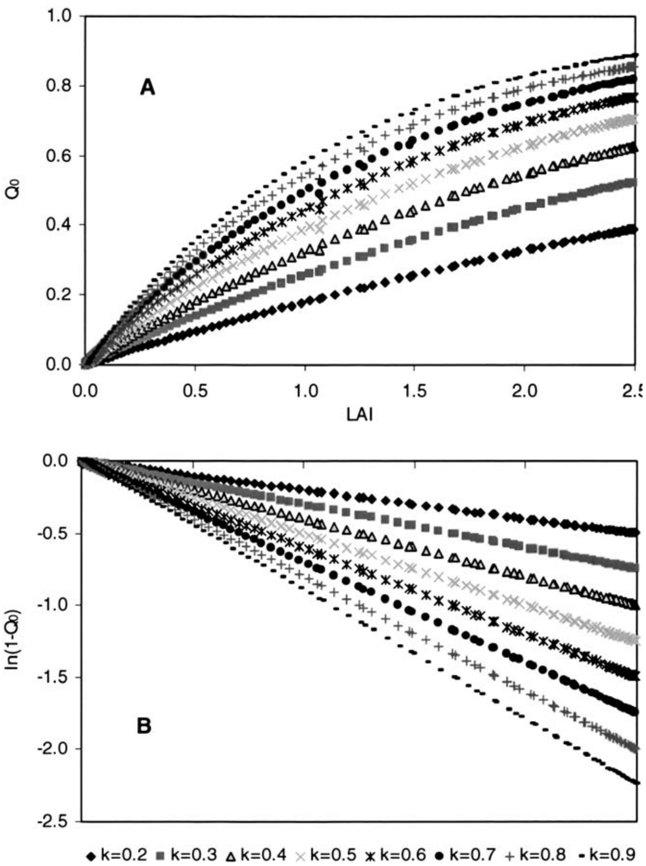

Fig. 4. (A) Ratio of the daily light energy intercepted by a crop canopy (Q_0) versus leaf area index (LAI) and (B) ln(1 − Q_0) versus LAI for different light extinction coefficient (k) values from 0.2 to 0.9.

light transmitted to the ground beneath the crop canopy, ln(1 − Q_0), was linearly related to LAI at the k value of 0.9 (Fig. 4B) in the same way described by Charles-Edwards et al. (1986). Therefore, the value of k was estimated as 0.9 (Ko, 2004). The k value is slightly higher than the values reported by Rosenthal and Gerik (1991) and by Steglich et al. (2000). However, it is in agreement with the range of k value for the plants with horizontal leaves hypothesized by Rosenberg et al. (1983).

The daily LAI increase (ΔL) with new leaf growth is calculated as follows:

$$\Delta L = \Delta M \cdot P_1 \cdot S \qquad [4]$$

where ΔM is the daily increase in AGDM from Eq. [2], P_1 is the fraction of ΔM partitioned to new leaves, and S is the specific leaf area (SLA) of the leaf tissues (Maas, 1993a). The SLA was determined from the relations between leaf dry weight and LAI (Reddy et al., 1989; Rhoads and Bloodworth, 1964). The slope of the linear equation obtained with data from Field #26, #28, and #33 is an estimate of SLA, which is 0.01 $m^2\ g^{-1}$ (Ko, 2004). The value is slightly lower than the values (0.014–0.027 $m^2\ g^{-1}$) reported from previous studies (Reddy et al., 1989; Rhoads and Bloodworth, 1964). The dimensionless leaf-partitioning fraction (P_1) is calculated using the equation:

$$P_1 = \mathrm{Max}(1 - a \cdot e^{b \cdot D}, 0) \qquad [5]$$

where a and b are parameters that control the magnitude and shape of the function and D is the cumulative GDD (Maas,

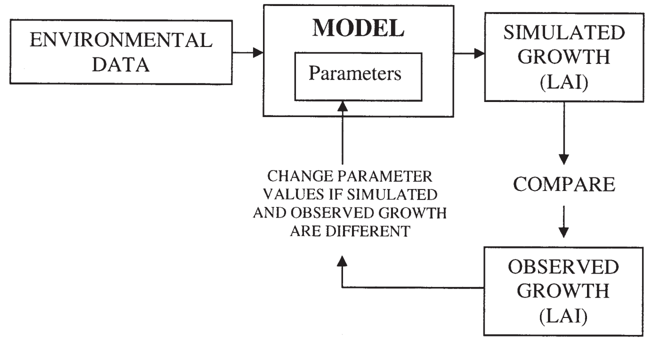

Fig. 5. Diagrammatic representation of how measured crop growth is used to calibrate the model parameters that affect simulated crop growth (after from Maas, 1993b). LAI, leaf area index.

1993a). This function reduces the partitioning of new dry mass to leaves as the plant approaches the reproductive phase.

The leaf senescence used in the model was formulated to describe the loss of leaf area based on environmental conditions. Leaf senescence (L_s, $m^2\ m^{-2}$) in the model is determined using the equation:

$$L_s = c \cdot (\Delta M_R - \Delta M) \qquad [6]$$

where c is the parameter that controls LAI curve after maximum LAI and ΔM_R is daily maintenance respiration requirement converted to biomass, calculated using the equation:

$$\Delta M_R = 0.03 \cdot M \qquad [7]$$

where M is total AGDM. In the model, an amount of LAI equal to L_s is deducted from the simulated canopy whenever the maintenance respiration exceeds the resources required for growth of existing tissues.

The daily increase in boll number (ΔB) used in this version of the model depends on accumulated GDD and LAI and is calculated with the following equation:

$$\Delta B = \gamma \cdot D \cdot \Delta f \qquad [8]$$

where γ is a fraction of boll production, D is accumulated GDD, and Δf is daily boll production efficiency affected by LAI. It is assumed that cotton boll numbers increase linearly depending on accumulated GDD and canopy growth. The γ value was estimated using data from Field #26 as the slope of the increase in boll numbers versus accumulated GDD. The value of γ is 0.57 $GDD^{-1}\ m^{-2}$ (Ko, 2004). The corresponding value was used as fruiting site production rate (FSPR) in the COTTAM model, which was 0.013 $site^{0.5}\ GDD^{-1}\ plant^{-1}$ for Paymaster based on the T_b of 12°C (Jackson et al., 1988). It is assumed that cotton boll numbers increase linearly depending on accumulated GDD and/or canopy growth. The Δf is calculated by the equation:

$$\Delta f = (\Delta L/\Delta G)/\lambda \qquad [9]$$

where λ is a parameter that affects daily boll production and ΔL/ΔG is the rate of LAI increase per accumulated GDD. The λ value was estimated using data from Field #28 as the slope of the increase in LAI versus accumulated GDD. The value of λ is 0.0058 GDD^{-1} (Ko, 2004).

The proposed cotton model uses the same within-season calibration procedures (Fig. 5) used in GRAMI, in which the simulated crop growth is compared with measured values. If the simulated values do not agree with the measured ones, an iterative numerical process is used to manipulate parameter values to improve agreement between the simulation and the

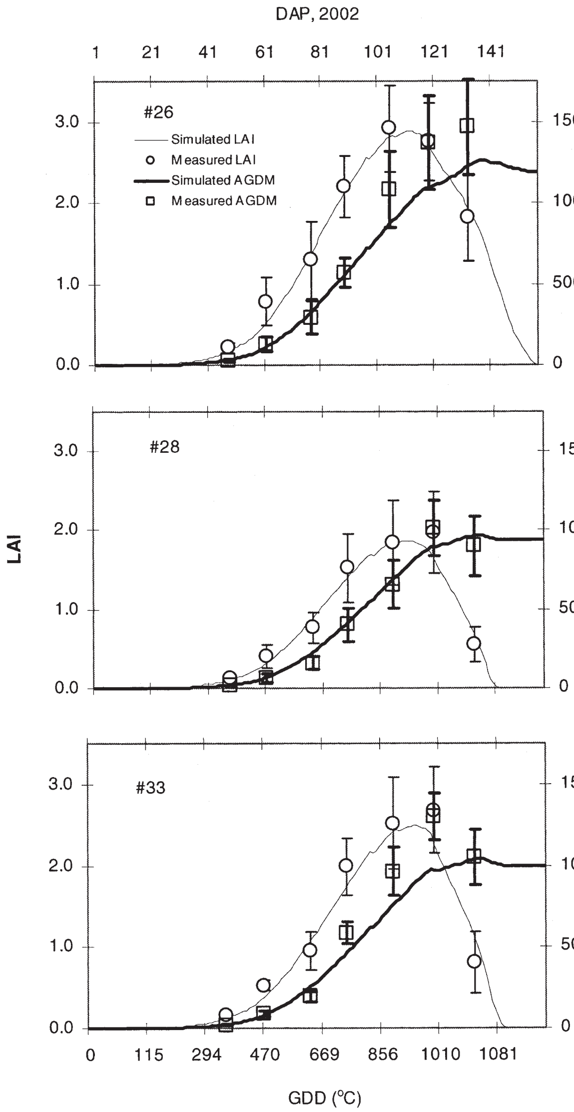

Fig. 6. Simulated leaf area index (LAI) and aboveground dry mass (AGDM) versus measured LAI and AGDM as a function of cumulative growing degree days (GDD) and days after planting (DAP) in Fields #26, #28, and #33. Vertical bars represent error above and below the mean within a 95% confidence interval (±2E).

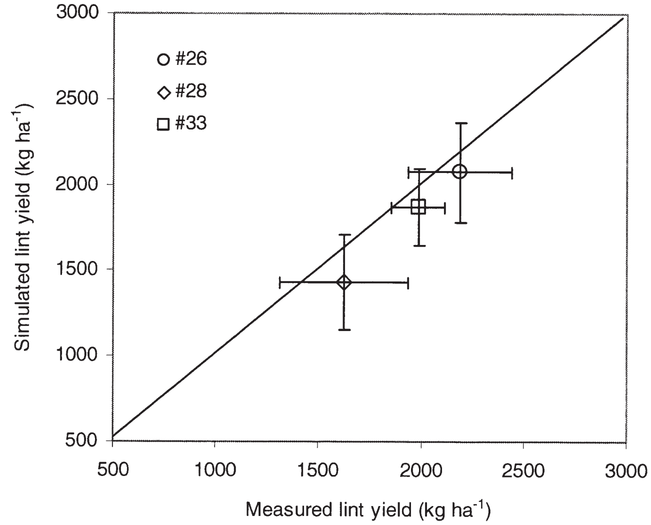

Fig. 7. Comparison between simulated and measured lint yield. Squares represent average values for each of the three fields. Horizontal bars represent error above and below the mean within a 95% confidence interval (±2E). Vertical bars represent variation of the mean. The solid diagonal line represents the 1:1 ratio.

measurements. The details of these procedures have been discussed by Maas (1993b).

There are four parameters (L_0, a, b, c) employed to control crop growth in the model. The initial values of L_0, a, b, and c before being calibrated are 2×10^{-7}, 3.25×10^{-1}, 1.25×10^{-3}, and 1.25×10^{-3}, respectively. The initial value (L_0) of LAI at crop emergence is determined in the first step in the model calibration. Then, a, b, and c are calibrated in order.

RESULTS AND DISCUSSION

Verification

The cotton model was used to simulate cotton growth and yield for the field data set used in model development. This was done to verify the performance of the model for the development data set. Field observations of LAI were used to calibrate the model rather than observations of remote sensing. Leaf area index or canopy GC of cotton can be estimated from remotely sensed scene reflectance obtained from a hand-held remote sensor (Maas, 1998) and from satellite data (Maas, 2000) using a linear mixture modeling approach. However, LAI estimation from plant sampling represents crop growths of experimental plots better than that from remotely sensed scene reflectance. Leaf area index data from plant sampling rather than remote sensing data was used in the model.

The results demonstrated that the model was able to reproduce the field observations of LAI and AGDM with reasonable accuracy (Fig. 6). While there were some inaccuracies in AGDM after 669 GDD in Fields #26 and #33, we believe that those are within acceptable ranges of measurement errors. Development of the model used in this study assumes that environmental and genetic factors affecting crop growth are expressed in the growth of the crop canopy. The GRAMI model (Maas, 1992, 1993a, 1993b) demonstrated that the assumption was generally appropriate. For crops with indeterminate growth habits, this expression may be less precise. However, in general, there were significant relationships between simulated and measured values for the three fields. In addition, simulated lint yields were in reasonable agreement with measured values for the three fields using the model (Fig. 7). These results indicated that the model appeared capable of reproducing irrigated cotton growth and yield over the growing season.

Validation

The accuracy of the model was tested using the independent data sets obtained at Lamesa and Lubbock.

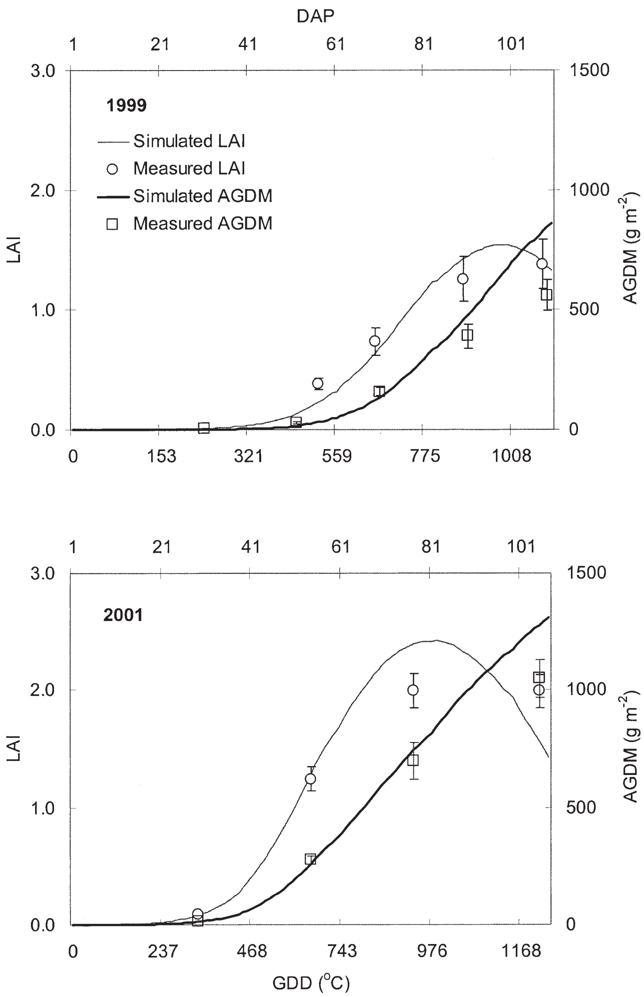

Fig. 8. Simulated leaf area index (LAI) and aboveground dry mass (AGDM) versus measured LAI and AGDM for the 1999 and 2001 data at Lamesa, TX. Vertical bars represent error above and below the mean within a 95% confidence interval (±2E). DAP, days after planting.

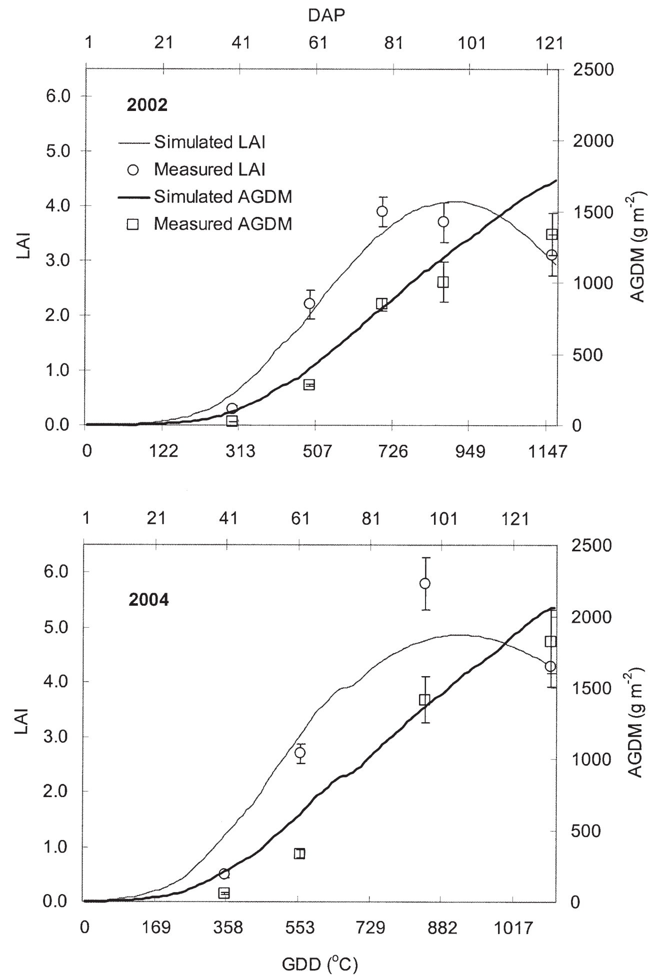

Fig. 9. Simulated leaf area index (LAI) and aboveground dry mass (AGDM) versus measured LAI and AGDM for the 2002 and 2004 data at Lubbock, TX. Vertical bars represent error above and below the mean within a 95% confidence interval (±2E). DAP, days after planting.

The simulated LAI curves were fit through the observations in a reasonable manner (Fig. 8 and 9). Simulated LAI values agreed with measured LAI values with an r^2 value of 0.92 and a root mean squared error (RMSE) of 0.19 for the Lamesa data sets and with an r^2 value of 0.94 and an RMSE of 0.35 for the Lubbock data sets. The resulting AGDM simulation also passed through the respective observations in a reasonable manner. Simulated AGDM values agreed with measured AGDM values with an r^2 value of 0.96 and an RMSE of 108.5 for the Lamesa data sets and with an r^2 value of 0.94 and an RMSE of 159.6 for the Lubbock data sets.

Simulated lint yields agreed with measured values with an r^2 value of 0.61 and an RMSE of 115.8 for both sites (Fig. 10). The 95% confidence interval (±2E) for yield was 124.5 kg ha^{-1} for the 1999 data and 153.1 kg ha^{-1} for the 2001 data at Lamesa and 112.1 kg ha^{-1} for the 2002 data and 150.9 kg ha^{-1} for the 2004 data at Lubbock. The variance of the corresponding simulated values showed 89.2 kg ha^{-1} for the 1999 data and 38.6 kg ha^{-1} for the 2001 data at Lamesa and 12.6 kg ha^{-1} for the 2002 data and 11.3 kg ha^{-1} for the 2004 data at Lubbock.

CONCLUSIONS

Simulated values of crop growth obtained with the new model showed reasonable agreement with corresponding measurements under irrigated field conditions. The proposed model has relatively simple environmental input requirements compared with other process-oriented cotton models. Since estimates of LAI used in calibrating the model may be obtained through remote sensing observations, it is potentially applicable for regional cotton growth monitoring and yield-mapping efforts.

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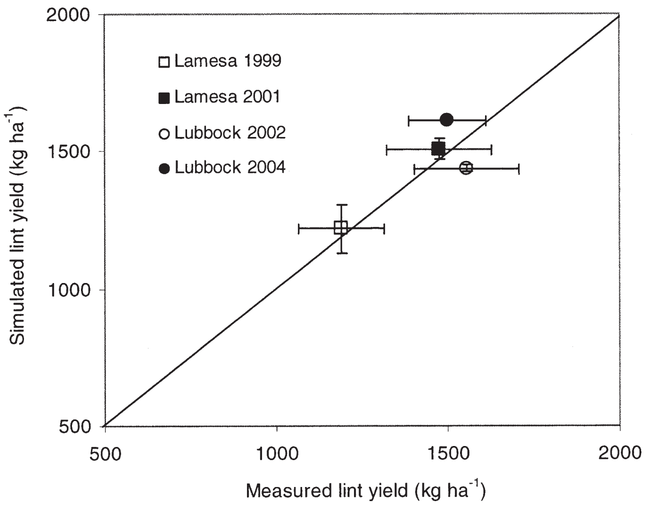

Fig. 10. Comparison between simulated and measured lint yield for the 2001 and 1999 data at Lamesa, TX and the 2002 and 2004 data at Lubbock, TX. Horizontal bars represent error above and below the mean within a 95% confidence interval (±2E). Vertical bars represent variation of the mean. The solid diagonal line represents the ratio 1:1.

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REFERENCES

Bronson, K.F., J.W. Keeling, J.D. Booker, T.T. Chua, T.A. Wheeler, R.K. Boman, and R.J. Lascano. 2003. Influence of landscape position, soil series, and phosphorus fertilizer on cotton lint yield. Agron. J. 95:947–957.

Charles-Edwards, D.A. 1982. Physiological determinants of crop growth. Academic Press, Orlando, FL.

Charles-Edwards, D.A., D. Doley, and G.M. Rimmington. 1986. Modeling plant and development. Academic Press, Orlando, FL.

Gallagher, J.N., and P.V. Biscoe. 1978. Radiation absorption, growth and yield of cereals. J. Agric. Sci. (Cambridge) 91:47–60.

Howell, T.A., and J.T. Musick. 1985. Relationships of dry matter production of field crops to water consumption. p. 247–269. *In* Les besoins en equ des cultures. Proc. Conf. Int., Paris. 11–14 Sept. 1984. INRA, Paris.

Jackson, B.S., G.F. Arkin, and A.B. Hearn. 1988. The cotton simulation model "COTTAM": Fruiting model calibration and testing. Trans. ASAE 31:846–854.

Jones, C.A., and J.R. Kiniry. 1986. CERES-MAIZE: A simulation model of maize growth and development. Texas A&M Univ. Press, College Station, TX.

Ko, J. 2004. Development of cotton crop model that uses remote sensing data. Ph.D. diss. Texas Tech Univ., Lubbock.

Li, H., R.J. Lascano, E.M. Barnes, J. Booker, L.T. Wilson, K.F. Bronson, and E. Segarra. 2001. Multispectral reflectance of cotton related to plant growth, soil water and texture, and site elevation. Agron. J. 93:1327–1337.

Maas, S.J. 1998. Estimating cotton ground cover from remotely sensed scene reflectance. Agron. J. 90:384–388.

Maas, S.J. 1992. GRAMI: A crop growth model that can use remotely sensed information. ARS-91. USDA, Washington, DC.

Maas, S.J. 1993a. Parameterized model of gramineous crop growth: I. Leaf area and dry mass simulation. Agron. J. 85:348–353.

Maas, S.J. 1993b. Parameterized model of gramineous crop growth: II. Within-season simulation calibration. Agron. J. 85:354–358.

Maas, S.J. 2000. Linear mixture modeling approach for estimating cotton canopy ground cover using satellite multispectral imagery. Remote Sens. Environ. 73:304–308.

Monteith, J.L., and M.H. Unsworth. 1990. Principles of environmental physics. 2nd ed. Edward Arnold, New York.

Reddy, V.R., B. Acock, D.N. Baker, and M. Acock. 1989. Seasonal leaf area—leaf weight relationships in the cotton canopy. Agron. J. 81:1–4.

Rhoads, F.M., and M.E. Bloodworth. 1964. Area measurement of cotton leaves by dry-weight method. Agron. J. 56:520–522.

Rosenberg, N.J., B.L. Blad, and S.B. Verma. 1983. Microclimate: The biological environment. 2nd ed. John Wiley & Sons, New York.

Rosenthal, W.D., R.L. Vanderlip, B.S. Jackson, and G.F. Arkin. 1989. SORKAM: A grain sorghum crop model. Misc. Publ. MP-1669. Texas Agric. Exp. Stn., College Station.

Rosenthal, W.D., and T.J. Gerik. 1991. Radiation use efficiency among cotton cultivars. Agron. J. 83:655–658.

Steglich, E.M., T.J. Gerik, J. Kiniry, J.T. Cothren, and R.G. Lemon. 2000. Change in the light extinction coefficient with row spacing in upland cotton. p. 606–608. *In* Proc. Beltwide Cotton Conf., San Antonio, TX. 6–9 Jan. 2000. Natl. Cotton Counc. of Am., Memphis, TN.

Wanjura, D.F., and J.R. Supak. 1985. Temperature methods for monitoring cotton development. p. 369–372. *In* Proc. Beltwide Cotton Conf., New Orleans, LA. 6–11 Jan. 1985. Natl. Cotton Counc. of Am., Memphis, TN.

Wanjura, D.F., D.R. Upchurch, and S. Maas. 2004. Spectral reflectance estimates of cotton biomass and yield. p. 838–851. *In* Proc. Beltwide Cotton Conf., San Antonio, TX. 7–9 Jan. 2004. Natl. Cotton Counc. of Am., Memphis, TN.